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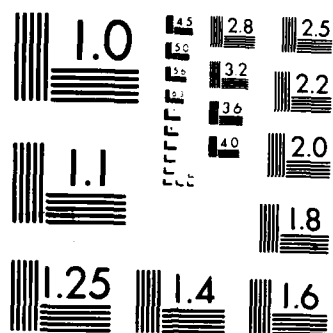
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FINAL REPORT

THEORETICAL PLASMA PHYSICS RESEARCH OF ACTIVE SPACE EXPERIMENTS

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The following report describes our present understanding and recent results from an analysis of the effects of elastic scattering on neutral beam penetration. As originally planned, the research described in the present report (Phase I) was to be continued contingent upon SDIO funding for neutral particle beam propagation studies.

Delays in the funding as well as the death of one of the principal investigators, Dr. Young-Ping Pao, has resulted in a temporary interruption of our present research program.

Review of the Problem:

We now discuss the important factors affecting neutral beam propagation in the upper atmosphere at altitudes of 200-250 km. Two primary factors affecting the beam quality are the accuracy of beam collimation and the effect of collisions between the beam particles and the background atmospheric particles. A further factor is ionization of the beam particles in terms of radiation or waves and instabilities that may result from the collective interaction between the ionized beam particles and the charged particles in the background atmosphere.

Simple estimates indicate that the spread of the footprint of the neutral beam imposes a high degree of accuracy on the beam collimation. For instance, a footprint spread of a couple of meters over a travelled

distance of one kilometer requires a collimation accuracy of one degree. This is a stringent requirement on the design of a beam device, which may be solved by elaborate ion optics, multiple aperture, etc. For the purpose of our work, we shall assume that the neutral beam has been satisfactorily collimated and propose to study the dynamics of the neutral beam propagation.

We shall typically consider a neutral beam with a 20 kev kinetic energy and 100 mils/cm² pre-neutralization current, but our theoretical framework is general enough to accommodate much higher intensities.

The predominant factor in neutral beam dynamics is the scattering of beam particles by the background particles. At 200-250 km altitudes, the major atmosphere constituent is atomic oxygen with number densities in the range of $10^9 - 10^{10} \text{ cm}^{-3}$. Because of these low densities, collisions between the beam and the background particles are relatively infrequent over distances of kilometer ranges. Simple estimates show that only a few percent of the beam particles will be lost from its trajectory over a distance of one kilometer. Over longer distances, the effects will be more pronounced.

To secure a detailed quantitative description of the quality of the neutral beam as it travels along its trajectory, we have formulated the neutral beam problem in terms of the Boltzmann equation and have solved it by the methods of Knudsen iteration or integral iteration in rarefied gas dynamics.



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The collision terms in the Boltzmann equation contain terms both due to self-collisions among the beam particles and the beam-background collisions between the beam particles and the background atmospheric particles. The ratio of the self-collision frequency to the beam-background collision frequency is roughly $N_B \Delta V / NV$ where N_B is the beam particle number density, N is background number density, V is the beam velocity, while ΔV is the spread of beam particle velocity. Within the parameter range in consideration, this ratio is generally small and the self-collisions are therefore negligible. We therefore only consider the beam-background collisions.

To furnish the beam-background collision terms, we have chosen general atom-atom interaction models. Because of the high degree of accuracy imposed by the beam collimation, a rather accurate potential model must be used; the usual hard-sphere or power-law repulsive potential models are grossly inadequate since they do not produce the attractive Van der Waals force which prevails in atom-atom collisions. We use a Lennard-Jones type repulsive-attractive potential to include the Van der Waals force as well as the electron overlapping repulsion.

The form of collision terms for the Lennard-Jones potential is more complicated than those for the usual hard-sphere or power-law models. But for the present problem we make use of the fact that the beam kinetic energy is much higher than the interatomic potential energy (\sim several ev) so that most collisions will result in small velocity deflections. This small deflection approximation simplifies the collision terms and therewith the Boltzmann equation considerably.

Therefore the first part of our study of the neutral beam propagation consists of two steps: (1) derive the beam-background collision terms for the Boltzmann equation by using small velocity deflection approximation, and (2) solve the Boltzmann equation by Knudsen iteration method.

The second part of our study concerns the effects of ionization of beam particles. A small portion of the beam particles can be ionized by electron impact or charge-exchange collisions with the positive ions in the atmosphere. At the altitudes of 200-250 km, the number densities of these atmospheric charged particles are typically of the order of 10^5 cm^{-3} , so that only a minute fraction of the beam particles will be ionized. However, the ionized beam particles, though small in numbers, can interact electromagnetically with the earth's magnetic field and the background atmosphere (considered as a slightly ionized gas.) We would like to study the effects of this interaction in terms of generation of radiation, waves or instabilities as possible candidates for diagnostic signals.

Results:

We have calculated the effects of the elastic scattering between the beam particles and the neutral atmospheric particles on the penetration of the neutral particle beam. The beam particles are taken to be of atomic hydrogen in the the energy range of 50-150 Mev propagating in an atmosphere of atomic oxygen. A mathematical model has been set up and analytic results have been obtained.

Main Features of the Mathematical Model

1. Atmospheric density variation is included.

We incorporated the effect of the atmospheric density variation along the beam propagation path in our analysis by using the exponential model

$$N(z) = N(z_0) \exp \{ -[(z-z_0)/\lambda]^{3/4} \},$$

where N is the atmospheric number density, z is the altitude in kilometers, $z_0 = 150$ and $\lambda = 25.5$. This exponential interpolation agrees quite well with 1962 U.S. Standard atmosphere data in the 150-300 km altitude range.

2. A critical scattering cross-section σ_c is used instead of the total scattering cross-section σ_{tot} . We introduce the concept of critical angle θ_c at a point in question on the beam path sustained by the target area (of 1 m^2) according to the line-of-sight principle. The critical cross-section σ_c corresponds to all scatterings that produce a deflection angle $\theta \geq \theta_c$. Since particles with $\theta < \theta_c$ will survive the scattering in their ability to arrive at the target, the neglect of scatterings with $\theta < \theta_c$ provides a more realistic calculation of the beam penetration problem. Needless to say, the use of σ_c instead of σ_{tot} gives a more optimistic estimate of the penetration length.

3. Various interacting potentials are used. Since the interacting potential between the beam particle and the atmospheric particles are not completely known in such high energy range of 50 Mev - 150 Mev, we have used different forms of potentials such as the pure Coulumb, screened Coulumb and composite-power law potentials. The use of the pure Coulumb potential and the power law potentials is made possible by considering the critical cross-section σ_c where their total cross-section become infinite.

4. The initial beam divergence is assumed to be zero. We assume there to be no initial beam divergence in order to concentrate our effort in analytically evaluating the effects of elastic scattering on the beam penetration. A nonzero initial beam divergence can be incorporated into our model by numerical computation.

Numerical Results

Explicit formulae have been obtained in the cases of Coulumb and screened Coulumb potentials for the beam penetration rate P , the fraction of the beam particles that will survive collisions with the atmospheric particle and arrive at the target area.

Some conclusions from these formulae are presented in the following. Here ϕ is the angle between the beam path and the inward earth radial direction at the beam accelerator. The target altitude is 150 km and z_a is the altitude of the accelerator.

1. For pure Coulumb potential

$$P = 0.5, \quad z_a = 300 \text{ km}, \quad E = 50 \text{ Mev}, \quad \phi = 0$$

$$P \geq 0.75, \quad z_a = 450 \text{ km}, \quad E = 150 \text{ Mev}, \quad \phi \leq 45^\circ.$$

2. For screened Coulumb potential with a Thomas-Fermi screening factor

$$P \geq 0.75, \quad z_a = 300 \text{ km}, \quad E = 50 \text{ Mev}, \quad \phi \leq 45^\circ.$$

The results show a dependence on the potential models used in the calculation.

Future Plan

If continuing funding is possible, we plan to pursue the following work.

1. Incorporate the initial beam divergence into the calculation.
2. Calculate the composite-power law potential case.
3. Examine the effects of stripping collisions.
4. Provide a complete theoretical picture for the problem of neutral particle beam penetration in a rerefied atmosphere.

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